Hubble Constant at Intermediate Redshift using the CO-Line Tully-Fisher Relation

Yoshinori Tutui,[1,2] Yoshiaki Sofue,[1] Mareki Honma,[3] Takashi Ichikawa,[4] and Ken-ichi Wakamatsu[5]

[1] *Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181-8588, Japan*
Email: sofue@ioa.s.u-tokyo.ac.jp

[2] *NHK, Science Division, Jin-nan, Shibuya-ku, Tokyo 150-0041, Japan*

[3] *VERA Project Office, National Astronomical Obs. Japan Mitaka, Tokyo 181-8588, Japan*

[4] *Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan*

[5] *Department of Technology, Gifu University, 1-1 Yanagido, Gifu 501-11, Japan*

February 1, 2008

Abstract

We have determined distances and Hubble ratios for galaxies at intermediate redshifts, $cz \sim 10,000$ to 35,000 km s^{-1} , by applying the CO-line Tully-Fisher relation to our ^{12}CO ($J = 1-0$)-line observations using the Nobeyama 45-m telescope, and near-IR (NIR) photometry in the J and H bands using the 1.88-m telescope at Okayama Astrophysical Observatory. By averaging the Hubble ratios from J-band result, we obtain a Hubble constant of $H_0 = 60 \pm 10$ km s^{-1}Mpc^{-1} . We argue that the CO line-NIR TFR can be a complimentary method to the other methods for measuring distances of galaxies at intermediate and high redshifts.

Key words: Cosmology: Hubble constant — Galaxies: distances and redshifts — ISM: CO line

1 Introduction

The HI-line Tully-Fisher relation (TFR) has been established as one of the most reliable methods to determine the distances of galaxies, and has been successfully applied for detemining the Hubble constant at (Tully and Fisher 1977; Aaronson et al 1980; Giovanelli et al 1985, 1995; Haynes and Giovanelli 1986). The use of the CO lines has been proposed as a complimentary method to HI (Sofue 1992; Dickey & Kazes 1992; Sofue et al 1996). Compatibility between CO and HI linewidths has been confirmed for nearby galaxy samples (Schöniger & Sofue 1994, 1997; Lavezzi and Dickey 1998; Tutui & Sofue 1999; Tutui et al 2000).

The CO-line TFR has some advantages, particluarly at higher redshifts: Since the molecular-gas distribution in a galaxy is tightly correlated with the luminousity distribution, CO-line width can be properly compared with photometric luminosity. CO gas distributions are less affected by galaxy interactions and intracluster medium compared to HI, and the CO gas is not particularly defficient even in cluster-center galaxies (Kenney & Young 1988; Casoli et al. 1991), which enables us to apply the TFR to rich-cluster galaxies. These properties will be helpful to apply the TFR to high redshifts, at which the fraction of interacting and merging galaxies is supposed to be greater than at low redshifts. Since high-redshift galaxies are supposed to be more dusty than nearby galaxies, near-IR photometry will be more appropriate than optical. Thus, the CO-NIR TFR would be a promising method to determine distances of intermediate and high-redshift galaxies, and particularly for cluster galaxies at high redshifts.

In this paper we report the result of an extensive CO TFR program using the Nobeyama 45-m mm-wave telescope, and NIR photometry using a 1.88-m telescope at Okayama Observatory. The program has been performed as a pilot program to promote a more sensitive, higher resolution CO-NIR TFR project using the Nobeyama mm-wave Array, and an advanced array linked to the 45-m telescope. We obviously aim at obtaining basic data for higher-transition CO line TFR using the Atacama Large Mm-wave and sub-mm wave Array (ALMA) in the near future.

2 Observations

2.1 Sample selection

We selected isolated galaxies of normal morphology as a sample according to the following criteria.

(1) Redshift range of the sample was taken to be $cz = 10,000-20,000$ km s^{-1} in 1994/1995 observations, $cz = 20,000 - 30,000$ km s^{-1} in 1995/1996, and $cz = 30,000 - 50,000$ km s^{-1} in 1996/1997 observations. The CO data are published in Tuttui et al (2000) for discussion of CO and infrared properties of non-interacting IRAS galaxies at intermediatet redshifts.

(2) We selected relatively strong FIR-emission sources at 60 μm and 100 μm, typically greater than 1 Jy, which are supposed to be bright in the CO line. Such FIR luminous galaxies are supposed to be affetected by efficient star formaiton. For this reason, we use NIR luminosities, istead of blue luminosities, which may be strongly affected by the star formation. However, we also emphasize that the TFR applies to IRAS galaxies with much higher FIR luminosities (van Driel et al 1995).

(3) In order to minimize the effect of galaxy-galaxy interaction, we selected galaxies with normal morphology using DSS (STScI Digitized Sky Survey) images. Strongly interacting galaxies and mergers were not included. They are not likely be starburst galaxies.

(4) Since the half-power beam width (HPBW) of the NRO 45-m telescope was $15''$, galaxies whose position error listed in the NASA Extragalactic Database (NED) is less than $10''$ were selected. We also cross-checked the position using the DSS images. The $15''$-beam corresponds to $\sim$ 30 kpc at $z \sim 0.1$. Hence, we may safely assume that most of CO-emitting disks are covered by the beam.

(5) Since linewidths of the objects were expected to be about 200 to 500 km s^{-1} , we selected galaxies with recession velocity accuracy better than 100 km s^{-1} , in order to fit the band width (250 MHz) corresponding to $650(1+z)$ km s^{-1} . The recession velocity was taken from the IRAS redshift surveys by Strauss et al. (1992) and Fisher et al. (1995).

The CO and far-infrared properties of individual objects are described in detail in Tutui et al (2000). The objects were selected by their isolated and normal morphology. This makes contrast to the existing CO-observations from the literature, which are mostly for interacting/merging systems. Using these new data, Tutui et al (2000) have discussed the molecular-gas and dust properties of late-type galaxies at intermediate redshift. We stress that our sample presents the deepest CO observations of non-intreacting/non-merging IRAS galaxies at intermediate redshift. The galaxies are shown to have normal star-formation efficiency, normal color-color diagrams, and not particularly strong nuclear activity. However, they show smaller gas-to-dust ratio than usual (brighter) IRAS galaxies. Nevertheless, our IRAS selected sample could contain starburst galaxies, which would have higher luminosity comared to normal galaxies. However, we note that van Driel et al.(1995) have examined the TF relation for IRAS selected galaxies, and found little difference from the TF relation of normal galaxies. Since galaxies rich in CO are often rich in HI, one might wonder how mamy galaxies in this sample are detected in HI. However, in so far as we have checked by NED, there have been no HI detection.

2.2 CO-Line Observations

The observataions of the ^{12}CO($J = 1-0$) line were carried out using the 45-m telescope at the Nobeyama Radio Observatory as a long-term projects at NRO. The observations were carried out in January and December in 1994, January, March and December in 1995, January, February and December in 1996, and in January in 1997. The HPBW of the NRO 45-m telescope was $15''$ at the frequency of ^{12}CO($J = 1-0$) line, and the aperture and main-beam efficiencies were $\eta_{\rm a} = 0.35$ and $\eta_{\rm mb} = 0.50$, respectively. As the receiver frontends, we used cooled SIS (superconductor-insulator-superconductor) receivers. The receiver backends were 2048-channel wide-band acousto-optical spectrometers (AOS) with the band width of 250 MHz, which corresponds to a velocity coverage of $650(1+z)$ km s^{-1}, or 650 ($z = 0$) to 780 km s^{-1} ($z = 0.2$).

The center frequency was set at the 1024-th channel, which corresponded to 115.271204 $(1+z)^{-1}$ for each galaxy. The system noise temperature was 300 $-$ 800 K in the single side band at the observing frequencies. Calibration of the line intensity was made using an absorbing chopper in front of the receiver, yielding an antenna temperature ($T^*_{\rm A}$), corrected for both the atmospheric and antenna ohmic losses. Intensity scale of $T^*_{\rm A}$ was converted to the main-beam brightness temperature by $T_{\rm mb} = T^*_{\rm A}/\eta_{\rm mb}$. Subtraction of sky emission was performed by the on-off position switching, and an offset of off-position was $5'$ far from on-position. Antenna pointing of the NRO 45-m telescope was done by observing nearby SiO maser sources at 43 GHz every 60 to 90 minutes, where the two receiveres (115 and 43 GHz) are well aligned for this perpose. The pointing accuracy was better than $\pm 4''$ during the observations. The total observation time for the on/off position integrations and pointing was about 2 to 9 hours for individual galaxies, and the on-source integration time for each galaxy was 1 to 3 hours.

After flagging bad spectra, subtraction of the baseline was performed by applying the standard

procedure of linear-baseline fitting at both edges of individual spectra. Adjacent channels were binned to a velocity resolution of 10 km s^{-1}. The rms noise of the resultant spectra at velocity resolution of 10 km s^{-1} was 2 − 5 mK in T_A^*.

2.3 CO-line Profiles and Linewidths

We observed 51 galaxies at intermediate redshift of $cz \sim 10,000 - 50,000$ km s^{-1} and obtained CO-line profiles of 17 galaxies, as listed in Table 1. The observed CO-line profiles are shown in Fig. 1. These galaxies are the deepest CO-line sample of IRAS galaxies with non-interacting, normal morphology (Tutui et al. 2000). The detection probability is not high compared to the LIR galaxies, because the sample consists of very distant galaxies of normal morphology. CO luminosities for an assumed Hubble constant of about 60 km s^{-1} — Mpc^{-1}, as will be obtained in the later section, are comparable to those of high-mass spirals, and estimated molecular hydrogen mass of the galaxies is of the order of $10^9 M_\odot$ for a conversion factor of 2×10^{20} H_2 [K km s^{-1}]$^{-1}$.

— Table 1 —

— Fig. 1 —

We determined the CO linewidths at the 20% level of the peak intensity. Although the line profiles are noisy with typical S/N ratios of about 10, the linewidths are determined within the error of $\Delta W \sim 10$ to 20 km s^{-1}. Since the expected line shapes from rotating disks are not straightforward, like gaussian, no automatic algorithm has been applied. Instead, we judged the linesby eyes, and the errors were taken to be the uncertainty in the edge channels of lines. One channel after smoothing, as in the figure, is 10 km/s. Three galaxies, IRAS 02411+0354, IRAS 07243+1215 and IRAS 14210+4829, are found to be too crude for TF analyses. The CO linewidth is defined as

$$W_{\rm obs} \equiv c\,\frac{\Delta\nu}{\nu_{\rm obs}}, \qquad (1)$$

where $\Delta\nu$ is the linewidth in observed frequency and $\nu_{\rm obs}$ is the observed center frequency of the spectrometer. The results of the observations are listed in Table 2.

— Table 2 —

2.4 H and J-band Photometry

Besides the CO-line observations, we have obtained near-IR (NIR) photometry in the J and H-bands (Aaronson et al. 1980). In these NIR bands, the interstellar extinction in our Galaxy and target galaxies is greatly reduced compared to B-band. This is particularly helpful for the present galaxies, which were selected from IRAS bright galaxies for CO-line detections. NIR luminosity of IRAS Minisurvey galaxies is shown to be not significantly enhanced compared to the RSA sample (van Driel et al. 1995).

Surface photometry observations were made in 1999 January in J- (1.25 μm) and H-band (1.65 μm) using OASIS, a NIR spectroscopic and imaging camera attached to the Cassegrain focus of the 1.88-m reflector at the Okayama Observatory. The detector was NICMOS-3 which consists of 256 × 256 pixels. The seeing size was $1.7'' - 2.1''$ (FWHM), and the sky level was typically 16 mag in J-band and 14 mag in H-band. One pixel corresponded to $0.97''$, and the field-of-view was approximately $4'$. The exposure time per one frame was 30–80 seconds for J-band and 10–30 seconds for H-band, and total integration time was about 20 minutes for each band per one galaxy. The flux calibration was performed using the standard stars in J and H-bands presented by Hunt et al. (1998) before and after each observation of galaxies. Standard data processing (dark current subtracting, image shifting/combining and flat fielding) was performed with the IRAF software package, and subsequent surface photometry and image processing (e.g. sky subtraction and flux measurement) was performed with the SPIRAL package developed at the Kiso Observatory and incorporated into the IRAF system (Hamabe & Ichikawa 1992). Figure 2 shows the obtained J-band images.

— Fig. 2 —

We obtained J and H-band photometric observations for 12 galaxies out of the 17 CO-detected galaxies, and measured the total magnitude. However, IRAS 17517+6422 was found to be an interacting galaxy, we did not include this galaxy in our TF analysis. Also, PG0157+001 was found to be a quasar, and was not included. Hence, the TF analysis was applied to the rest 10 galaxies, as listed in Table 4.

We measured the integrated magnitude of galaxies within a circular annuli outward from the galaxy center with 1 pixel interval. We define the total magnitude as the converged value of the growth curve. The total magnitude thus defined have the error as large as 0.1 mag since the galaxy morphology is not well determined (de Vaucouleurs 1991).

The following corrections were applied to the observed total magnitude m_T to obtain corrected total magnitude m_T^0 is written as

$$m_T^0 = m_T - A_i - A_G - K(z),. \qquad (2)$$

Here, A_i is the internal extinction within the target galaxy, and was calculated from B-band value taken from RC3 (de Vaucouleurs et al. 1991; Watanabe et al. 1998) using a formula $A_i^J = 0.21 A_i^B$

and $A_i^H = 0.13 A_i^B$ (Rieke & Lebofsky 1985). The Galactic extinction A_G is taken from Berstein & Heiles (1982). The K-correction, a correction for a redshifted wavelength of observed passbands, is estimated by assuming the spectral model of Poggianti (1997) for an Sc galaxy. The corrected total magnitude m_T^0 in Eq.(2) was further corrected for the evolution, E-correction, adopted from Poggianti (1997). We defined the total magnitude corrected for K and E-corrections as m_T^1,

$$m_T^1 = m_T - A_i - A_G - K(z) - E(z). \tag{3}$$

The errors of the corrected magnitudes are assumed to be the same as those of the observed value m_T, 0.1 magnitude. The value of these corrections and the corrected magnitude are also listed in Table 3. The errors of the thus calculated corrected magnitudes are assumed to be the same as those for the observed value m_T, which is 0.1 magnitude.

— Table 3 —

3 Determination of the Hubble constant

3.1 Inclination correction

Since B-band images would be affected by recent star formation which disturbs the isophote in bluer bands, we used R-band images taken from the STScI Digitized Sky Survey for determination of the inclination angle, using the conventional formula given by Hubble (1926):

$$\cos^2 i = \frac{(b/a)^2 - \mathsf{q}_0^2}{1 - \mathsf{q}_0^2} \tag{4}$$

where b/a is the minor-to-major axial ratio and q_0 is an intrinsic axial ratio fixed to 0.2. The disk images of the sample galaxies in J and H bands are too faint against the high sky background to fit the major and minor axes. Therefore, we adopt the deeper optical R band images for obtaining the inclination.

3.2 Conversion of CO to HI linewidths

The inclination-corrected CO-line velocity width is then calculated as

$$W_{\rm CO}^c = \frac{W_{\rm obs}}{\sin i}, \tag{5}$$

where i is the inclination angle, and the suffix c denotes the corrected linewidth. Tutui & Sofue (1999) and Tutui (1999) showed, that the CO linewidth is not entirely identical with the HI linewidth:

$$W_{\rm HI}^c = 0.76\ W_{\rm CO}^c + 83.8. \tag{6}$$

The HI linewidth is slightly larger than CO width for slowly rotating galaxies, and vice versa for fast rotating galaxies. This is caused by different gas distribution in a galaxy and by velocity dependence on a shape of the rotation curve. These corrected linewidths are listed in Table 4. Note that, according to this equation, $W_{\rm HI}^c$ and $W_{\rm CO}^c$ coincide within the error for galaxies with typical line widths of around 350 km s^{-1} .

— Table 4 —

3.3 Adopted Tully-Fisher relations

We then apply the HI Tully-Fisher relation in J and H-bands derived by Watanabe et al (2001) for the thus corrected values of $W_{\rm HI}^c$. Watanabe et al. (2001) calibrated the TF relations using the local calibrators with the Cepheid distances observed by HST, where the zero-point calibrations were performed for the calibrators observed with the Kiso Observatory 105-cm Schmidt telescope. We obtain the total matnitude, the inclination, the extinction correction, and the line with in the same way as those of the calibrators.

$$M_{J_T} = -8.48(\pm 0.85)(\log W_{\rm HI}^c - 2.5) - 22.13(\pm 0.39) \tag{7}$$

$$(\sigma = 0.30), \tag{8}$$

and

$$M_{H_T} = -7.54(\pm 0.76)(\log W_{\rm HI}^c - 2.5) - 22.95(\pm 0.35) \tag{9}$$

$$(\sigma = 0.28). \tag{10}$$

3.4 Determination of Hubble constant

Luminosity distance derived from the TFR is given by the distance modulus, $m - M$, as

$$\log D_L = -5 + \frac{1}{5}(m - M) \ \ (\mathrm{Mpc}), \tag{11}$$

where m is apparent total magnitude. The luminosity distance is related to the Hubble constant as

$$D_L = \frac{c}{H_0 q_0^2} \left\{ q_0 z + (q_0 - 1)(\sqrt{2 q_0 z + 1} - 1) \right\}, \tag{12}$$

where q_0 is the deceleration parameter, and we take $q_0 = 0.5$. Then, the Hubble ratio is written as,

$$H_0 = \frac{2c}{D_L}(z + 1 - \sqrt{z+1}), \tag{13}$$

For small redshift, $z \ll 1$, this relation reduces, of course, to $H_0 = cz/D_L$. The obtained Hubble ratios for all sample galaxies is listed in Table 5.

— Table 5 —

The distances and Hubble ratios derived from the Tully-Fisher relations are listed in Table 5, dand the J and H-band results after K correciton are plotted in Fig. 3. We, then, calculated the mean Hubble constant in the observed redshift range by weight-averaging the individual values, which the results are listed in Table 6. Thereby, values exceeding 3σ dispersion of the plots are excluded. Namely, two galaxies, IZw 23, CGCG 1113.7+2936, as well as the quasar PG 0157 were excluded from the sample. Note that the plots in Fig. 3 and are more scattered for lower redshift galaxies, for which the beam size ($15''$) could not cover the whole CO emitting regions.

—- Table 6 —-

—- Fig. 3 —-

The weighted mean value of the Hubble ratios from the J-bands results after K correction is obtained to be $H_0 = 60 \pm 10$ km s^{-1} Mpc^{-1}. The H band result leads to $H_0 = 53 \pm 13$ km s^{-1} Mpc^{-1}. The Hubble ratios for J and H-band are almost equal for some galaxies, confirming that the uncertainty in surface photometry in J and H-band is small. The K-and-E corrected Hubble constant is determined as $H_0 = 58 \pm 10$ km s^{-1} Mpc^{-1} in J-band, and $H_0 = 52 \pm 12$ km s^{-1} Mpc^{-1} in H-band, which are only 3% smaller than the value after the K correction alone.

3.5 Errors

Given a TF relation, the error in the absolute magnitude ΔM arises from the errors in the CO linewidth $\Delta W_{\rm obs}$, inclination Δi, and redshift Δz, which propagate to each other as follows.

$$\Delta M = \sqrt{\left(\frac{\Delta W_{\rm obs}}{W_{\rm obs}}\right)^2 + \left(\frac{\Delta i}{\tan i}\right)^2 + \left(\frac{\Delta z}{1+z}\right)^2} \cdot |A| \log e, \tag{14}$$

where A is the slope of the TFR. The error in the luminosity distance is, then, related to the error in the absolute magnitude as above, and the error in the apparent magnitude measurement:

$$\frac{\Delta D_L}{D_L} = \frac{\Delta(m-M)}{5\log e} = \frac{1}{5\log e}\sqrt{\Delta m^2 + \Delta M^2} \tag{15}$$

and

$$\frac{\Delta D_L}{D_L} = \frac{1}{5\log e} \times \tag{16}$$

$$\sqrt{\Delta m^2 + \left\{\left(\frac{\Delta W_{\rm obs}}{W_{\rm obs}}\right)^2 + \left(\frac{\Delta i}{\tan i}\right)^2 + \left(\frac{\Delta z}{1+z}\right)^2\right\} |A|^2 (\log e)^2}. \tag{17}$$

For small redshift, the error in Hubble ratio is written as,

$$\frac{\Delta H_0}{H_0} = \sqrt{\left(\frac{\Delta z}{z}\right)^2 + \left(\frac{\Delta D_L}{D_L}\right)^2}. \tag{18}$$

The contribution of the errors in total magnitude Δm and redshift Δz to the error of the distance estimation is much smaller than that of the errors of linewidth $\Delta W_{\rm obs}$ and inclination Δi, which was measured to be about $4^\circ.8$ for all galaxies. Therefore, the first and 4th terms in the square root of Eq. (14) are negligible compared to the other terms. The error in the resultant Hubble ratio increases with decreasing linewidth. The beam-size effect is crucial for lower redshift galaxies: It may happen that the telescope beam cannot cover the entire CO extent for large angular diameter galaxies. The telescope beam ($15''$) corresponds to 36 kpc for a galaxy at $cz = 30,000$ km s^{-1} for our resulting Hubble constant of about 60 km s^{-1} Mpc^{-1}. This diameter covers the substantial portion of the interstellar gas disks, and the detected CO line well represents the maximum velocity width. However, for lower redshift galaxies than 15,000 km s^{-1} , for example, the beam might not cover the entire disk, which may result in underestimation of the line width, and therefore, underestimation of the Hubble ratio. In fact, the scatter of the plot in Fig. 3 increases with decreasing redshift, implying the beam effect for low redshift galaxies would not be negligible. The result would be, therefore, more reliable for galaxies at $cz > 20,000$ km s^{-1} in the present case for the 45-m telescope.

4 Discussion

Peculiar velocities of galaxies, either individual or due to large-scale structures in clusters and networks, contribute significantly to the scatter in Hubble ratios. Therefore, in order to obtaine a more accurate Hubble constant, it is important to go to higher redshifts where the peculiar velocities are small compared to the recession velocity. On the other hand, the evolution effect becomes significant at higher redshift, which is still not easy to correct for by the current models. These confilicting requirements can be optimized by applying the TFR to galaxies at intermediate redfhits. For such purposes, the CO TFR would potentially be an alternative to HI TFR, particularly when larger and more sensitive facilities such as the ALMA becomes available in the future.

We have thus shown that the CO TFR is quite possible in the cosmological distances at $cz \sim 10,000 - 50,000$ km s^{-1}, although the detectability

and the accuracy are not satisfactory yet. Nevertheless, we were able to determine the mean Hubble constant in the space between $cz \sim 10,000$ and $35,000$ km s^{-1} to be $H_0 = 60 \pm 10$km s^{-1}Mpc^{-1} from the J-band TFR.

Our value is consistent within the error with the recent value $H_0 = 65$ km s^{-1}Mpc^{-1} from HI TFR at $cz < 12000$ km s^{-1} (Watanabe et al. 1998), and is slightly smaller thatn that from the HST key project, $H_0 = 71$ km s^{-1}Mpc^{-1} , for galaxies within 25Mpc and clusters within 10,000 km s^{-1} (Mould et al. 2000). Our value is also consistent with those obtained at similar redshifts using Type I supernovae (Sakai et al. 2000; Branch et al. 1998), those using the Sunyaev-Zel'dovic (1972) effect (Hughes and Birkinshaw 1998), and those from gravitationally lensed QSOs (Williams et al. 2000). In Fig. 4 we plot the recent values of Hubble constants derived from various methods, following Okamura (1999). Vertical bars indicate errors, and horizontal bars the redshift coverage.

— Fig. 4 —

We emphasize that the present CO-line method provides us with an alternative, new tool to estimate the distances of intermediate-redshift galaxies in the scheme of the established Tully-Fisher relation. The thus obtained Hubble constant can be directly compared with those obtained for nearer galaxies using the TFR.

We finally stress that the CO-NIR TFR will be a promising tool for high-redshift galaxies, which are supposed to be dusty, if the evolutionry effect can be properly corrected. The CO-NIR TFR as proposed in this paper will become one of the methods for cosmological distance estimates at high redshifts using the coming largest mm- and sub-mm wave facility, ALMA, by which higher transition CO lines will be observed with much higher sensitivity. The present project using the 45-m telescope has been performed in order to establish a methodology of the CO TFR, and to evaluate the feasibility for future projects using the Nobeyama mm-wave Array and ALMA.

YT and MH would like to thank the Japan Society for the Promotion of Science for the financial support for young researchers. IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

References

Aaronson, M., Huchra, J., Mould, J. 1980, ApJ, 237, 655

Berstein, D., Heiles, C. 1982, AJ, 87, 1165

Branch, D. 1998 ARA&A 36, 17.

Casoli, F., Boisse, P., Combes, F., Dupraz, C. 1991, A&A, 249, 359

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G.,Jr., Buta, R.J., Paturel, G., Fouqué, P. 1991 *Third Reference Catalog of Bright Galaxies (RC3)* (New York: Springer-Verlag)

Dickey, J. M., Kazes, I. 1992, ApJ 393, 530

Eastman, R. G., Schmidt, B. P., Kirshner, R. 1996, ApJ, 466, 911

Fisher, K. B., Huchra, J. P., Strauss, M. A., Davis, M., et al. 1995, ApJS, 100, 69

Furuzawa, T., Tawara, Y., Yamashita, K., Miyoshi, S. 1997, IAU Symp. 183, 70

Giovanelli, R., Haynes, M. P. 1985, ApJ, 292, 404

Giovanelli, R., Haynes, M. P., Salzer, J. J., Wegner, G., Da Costa, L. N., Freudling, W. 1995, AJ, 110, 1059

Hamabe, M., and Ichikawa, S. 1992, in A.S.P. Conference Ser. Vol. 25, Proc. Astronomical Data Analysis Software and Systems I, ed. D. M. Worrall et al. (San Francisco: Astronomical Society of the Pacific), 325

Haynes, M. P., Giovanelli, R. 1986, ApJ, 306, 466

Hubble, E. P. 1926, ApJ, 64, 321

Hughes, J. P., and Birkinshaw, M. 1998 ApJ 501, 1

Hunt, L. K., Mannucci, F., Testi, L., Migliorini, S., Stanga, R. M., Baffa, C., Lisi, F., Vanzi, L. 1998 AJ, 115, 2594.

Jacoby, G. H. 1997, in *The Extragalactic Distance Scale*, eds. Livio, M. et al. (Cambridge: Cambridge University Press) p.197

Kenney, J. D., Young, J. S. 1988, ApJS 66, 261

Lavezzi, T. E. and Dicky, J. 1998 AJ 116, 2672

Mould, J. R., Huchra, J. P., Freedman, W. L., Kennicutt, R. C. Jr., Ferrarese, L., Ford, H. C., et al. 2000, ApJ, 529, 786

Okamura, S. 1999, in *Milky Way Galaxy and the Universe of Galaxies* (Tokyo: University of Tokyo Press) p.203

Poggianti, B. M. 1997, A&AS, 122, 399

Rieke, G. H., Lebofsky, M. J. 1985, ApJ, 288, 618

Riess, A. G., Press, W. H., Kirshner, R. P. 1995, ApJ, 438, L17

Sakai, S., Mould, J. R., Hughes, S. M. G., Huchra, J. P., Macri, L. M., Kennicutt, R. C. Jr. et al. 2000, ApJ, 529, 698

Sandage, A., Saha, A., Tammann, G. A., Labhardt, L., Panagia, N., Macchetto, F. D. 1996, ApJ, 460, L15

Schöniger, F., Sofue, Y., 1994, A&A 283, 21

Schöniger, F., Sofue, Y., 1997, A&A 323, 14

Sofue, Y., 1992, PASJ 44, L231

Sofue, Y., Schöniger, F., Honma, M., Tutui, Y., Ichikawa,, T., Wakamatsu, K., Kazes, I. & Dickey, J. 1996 PASJ 48, 657-670

Strauss, M. A., Huchra, J. P., Davis, M., Yahil, A. et al. 1992, ApJS, 83, 29

Sunyaev, R.A. & Zel'dovich, Ya.B. 1972, in *Comm. Astrophys. Space. Phys.,* 40, 173

Tanvir, N. R., Shanks, T., Ferguson, H. C., Robinson, D. R. T. 1995, Natur, 377, 27

Tonry, J. L. 1991, ApJ, 373, L1

Tutui, Y. & Sofue, Y. 1997, A&A 326, 915

Tutui, Y., & Sofue, Y. 1999, A&A, 351, 467

Tutui, Y. 1999, in *the Ph.D. thesis of the University of Tokyo*

Tutui, Y., Sofue, Y., Honma, M., Ichikawa, T., Wakamatsu, K. 2000 PASJ 52, 803.

Van Driel, W., Van Den Broek, A. C., Baan, W. 1995, ApJ, 444, 80

Watanabe, M., Ichikawa, T., Okamura, S. 1998, ApJ, 503, 553

Watanabe, M., Tasuda, N., Itoh, N. Ichikawa, T., & Yanagisawa, K. 2001, ApJ, in press

Williams L. L. R. and Saha, P. 2000, AJ, 119, 439

Figure Captions

Fig. 1. CO line profles for 17 galaxies. The horizontal bars indicate the measured line widths. Galaxiese with asterisques are for marginal and non-detection, which are not included in the distance estimation.

Fig. 2. J and H-band images of the measured galaxies. mage sizes are $1' \times 1'$ except for for NGC 6007 of $2' \times 2'$. Faintest isophote is 22 mag arcsec^{-2} for J-band, and 20 mag arcsec^{-2} for H-band. Contour intervals is 1 mag arcsec^{-2}. Top is to the north, and left to the east.

Fig. 3. Hubble ratios plotted against redshifts for J- (filled circles) and H-band (diamonds), after K correction. Note the smaller scatter for larger redshifts than $\sim$ 20000 km s^{-1} .

Fig. 4. Hubble constants determiend by various methods (Okamura 1999). The references are: SBF (surface brightness fluction: Tonry 1991); PNLF (planetary nebulae luminosity function: Jacoby 1997); HST (The HST key project: Sakai et al. 2000); Cepheid (Tanvir et al. 1995); TF (Watanabe et al. 1999); SN II (Type II SN: Eastman et a. 1996); SN Ia(R) (Type Ia SN: Riess et al. 1995); SN Ia(S) (Type Ia SN: Sandage et al. 1996; GL (Gravitaional Lens: kundic et al. 1997); SZ (Sunyaev-Zeldóvich effect: Furuzawa 1997); and COTF (This work).

Table 1. Galaxies detected in the CO-line using the NRO 45-m telescope.

Galaxy (IRAS ID)	RA_{1950} h m s	Dec_{1950} ° ′ ″	cz km s^{-1}	z	D_{cz} Mpc	J-band size ″×″
PG 0157+001 (01572+0009)	01 57 16.3	+00 09 09	48869	0.16301	677	24x15
IRAS 02185+0642	02 18 40.3	+06 43 03	29347	0.09789	401	19x17
IRAS 02411+0354†	02 41 09.3	+03 53 56	43050	0.14360	594	
IRAS 07243+1215†	07 24 20.6	+12 15 09	28204	0.09408	385	
I Zw23 (09559+5229)	09 56 01.0	+52 29 48	12224	0.04077	165	31x25
CGCG 1113.7+2936 (11137+2935)	11 13 47.1	+29 35 58	13880	0.04630	187	50x31
IC 2846 (11254+1126)	11 25 24.8	+11 26 01	12294	0.04101	166	46x27
IRAS 14060+2919	14 06 04.9	+29 18 59	35060	0.11695	481	17x11
CGCG 1417.2+4759 (14172+4758)	14 17 14.8	+47 59 00	21465	0.07160	291	25x21
IRAS 14210+4829†	14 21 06.2	+48 29 59	22690	0.07569	308	
CGCG 1448.9+1654 (14488+1654)	14 48 54.5	+16 54 02	13700	0.04570	185	23x19
NGC 6007 (15510+1206)	15 51 01.6	+12 06 27	10547	0.03518	142	85x43
IRAS 16533+6216	16 53 19.8	+62 16 36	31808	0.10610	435	13x12
PGC 60451 (17300+2009)	17 30 00.6	+20 09 49	14989	0.05000	202	
IRAS 17517+6422	17 51 45.0	+64 22 14	26151	0.08723	356	
IRAS 23389+0300	23 38 56.9	+03 00 48	43470	0.14500	600	
IRAS 23420+2227	23 42 00.6	+22 27 50	26022	0.08680	354	15x10

Col.(1): Galaxy name. A dagger denotes a galaxy of marginal detection. Col.(2): Alias of the galaxy name as the IRAS catalog name. Col.(2) and (2): Coordinates in B1950. Col.(4): Heliocentric velocity. Col.(5): Heliocentric redshift from Fisher et al. (1995). Col.(6): Distance derived from the redshift, assuming $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. Col.(7): J-band angular size in arc seconds for galaxies observed in the present photometry imaging.

Table 2. CO-line observation results using the NRO 45-m telescope.

Galaxy	cz km s^{-1}	$t_{\rm int}$ min.	r.m.s. mK	$W_{\rm obs}$ km s^{-1}	$T_{\rm A}^{*}$ mK	$I_{\rm CO}$ K km s^{-1}	
PG 0157+001	48869	90	2	300 ± 15	15	5.11	(0.22)
IRAS02185+0642	29347	90	4	356 ± 15	40	13.05	(0.48)
IRAS02411+0354†	43050	60	5	—-	8	1.90	(0.66)
IRAS07243+1215†	28204	90	3	—-	6	1.79	(0.28)
IZw23	12224	60	4	104 ± 5	39	4.82	(0.26)
CGCG1113.7+2936	13880	60	5	248 ± 20	14	4.33	(0.55)
IC2846	12294	30	4	360 ± 20	19	4.78	(0.48)
IRAS14060+2919	35060	120	3	376 ± 20	8	1.91	(0.37)
CGCG1417.2+4759	21465	180	3	293 ± 15	13	4.66	(0.32)
IRAS14210+4829†	22690	60	4	—-	11	3.08	(0.54)
CGCG1448.9+1654	13700	60	4	282 ± 10	28	7.03	(0.42)
NGC6007	10547	60	7	347 ± 10	28	11.24	(0.82)
IRAS16533+6216	31808	90	3	217 ± 10	10	3.54	(0.28)
PGC60451	14989	60	7	459 ± 15	20	10.35	(0.95)
IRAS17517+6422	26151	90	5	480 ± 20	19	4.00	(0.69)
IRAS23389+0300	43470	180	3	272 ± 20	8	3.92	(0.31)
IRAS23420+2227	26022	60	7	308 ± 20	15	4.80	(0.49)

Col.(1): Galaxy name. A dagger denotes a galaxy of marginal detection. Col.(2): Redshift in cz. Col.(3): Integration time of on-source in minute. Col.(4): Root mean square of antenna temperature after binning of 10 km s^{-1} in emission-free region of the spectrum. Col.(5): Observed CO linewidth defined as the full width at 20% of the maximum intensity. Col.(6): Antenna temperature at the peak level intensity. Col.(7): Integrated intensity corrected for the main beam efficiency. Col.(8): Uncertainty of 1 σ in the integrated intensity.

Table 3. Total magnitude and correction for magnitude.

Galaxy	m_T mag	A_i mag	A_G mag	K mag	E mag	m_T^0 mag	m_T^1 mag
(J-band)							
PG 0157+001	14.23	0.02	0.04	-0.09	-0.17	14.26	14.43
IRAS 02185+0642	14.37	0.02	0.04	-0.06	-0.10	14.37	14.47
I Zw23	12.77	0.02	0.04	-0.03	-0.05	12.74	12.79
CGCG 1113.7+2936	13.41	0.05	0.03	-0.04	-0.05	13.37	13.42
IC 2846	12.26	0.03	0.04	-0.03	-0.05	12.21	12.26
IRAS 14060+2919	15.10	0.03	0.03	-0.07	-0.12	15.11	15.23
CGCG 1417.2+4759	13.89	0.02	0.04	-0.05	-0.08	13.88	13.96
CGCG 1448.9+1654	14.12	0.02	0.04	-0.03	-0.05	14.09	14.15
NGC 6007	12.66	0.03	0.05	-0.03	-0.05	12.61	12.66
IRAS 16533+6216	15.16	0.02	0.05	-0.07	-0.14	15.15	15.29
IRAS 23420+2227	15.64	0.03	0.04	-0.06	-0.10	15.63	15.73
(H-band)							
PG 0157+001	13.32	0.01	0.02	-0.08	-0.16	13.37	13.53
IRAS 02185+0642	13.18	0.02	0.03	-0.04	-0.10	13.17	13.27
I Zw23	12.26	0.01	0.03	-0.02	-0.04	12.24	12.28
CGCG 1113.7+2936	12.34	0.03	0.02	-0.02	-0.05	12.31	12.36
IC 2846	11.49	0.02	0.02	-0.02	-0.04	11.47	11.51
IRAS 14060+2919	14.57	0.02	0.02	-0.05	-0.12	14.58	14.70
CGCG 1417.2+4759	13.32	0.01	0.02	-0.03	-0.08	13.31	13.39
CGCG 1448.9+1654	13.98	0.02	0.02	-0.02	-0.05	13.96	14.01
NGC 6007	12.37	0.02	0.03	-0.01	-0.04	12.33	12.37
IRAS 16533+6216	14.52	0.01	0.03	-0.04	-0.11	14.52	14.63
IRAS 23420+2227	14.91	0.02	0.02	-0.04	-0.09	14.90	14.99

Col.(1): Galaxy name. Col.(2): Observed total magnitude. Col.(3): Internal extinction. Col.(4): The Galactic extinction. Col.(5): K-correction. Col.(6): E-correction. Col.(7): Corrected total magnitude without E-correction written by $m_T^0 \equiv m_T - A_i - A_G - K$. Col.(8): Corrected total magnitude written by $m_T^1 \equiv m_T - A_i - A_G - K - E$.

Table 4. Linewidths and total magnitudes.

Galaxy	cz km s^{-1}	i deg	$W_{\rm CO}$ km s^{-1}	$W^c_{\rm CO}$ km s^{-1}	$W^c_{\rm HI}$ km s^{-1}	$m^0_{\rm T}(J)$ mag	$m^1_{\rm T}(J)$ mag	$m^0_{\rm T}(H)$ mag	$m^1_{\rm T}(H)$ mag
IRAS 02185+0642	29347	33	356	654	581	13.85	13.95	13.17	13.27
I Zw23	12224	49	104	138	189	12.74	12.79	12.24	12.28
CGCG 1113.7+2936	13880	58	248	293	306	13.37	13.42	12.31	12.36
IC 2846	12294	34	360	644	573	12.21	12.26	11.47	11.51
IRAS 14060+2919	35060	47	376	514	475	15.11	15.23	14.58	14.70
CGCG 1417.2+4759	21465	44	293	422	404	13.88	13.96	13.21	13.29
CGCG 1448.9+1654	13700	40	282	439	417	14.09	14.15	13.96	14.01
NGC 6007	10547	43	347	509	471	12.61	12.66	12.33	12.37
IRAS 16533+6216	31808	27	217	478	447	15.15	15.29	14.52	14.63
IRAS 23420+2227	26022	51	308	396	385	15.63	15.73	14.90	14.99

Col.(1): Galaxy name. Col.(2): Redshift in cz. Col.(3): Inclination. The inclination errors were measured to be about $4^\circ.8$ for all galaxies, and we adopted the same value through this paper. Col.(4): CO linewidth. Col.(5): CO linewidth corrected for the inclination. Col.(6): Converted CO linewidth corresponding to HI linewidth. Col.(7): Total magnitude defined as $m_T^0 \equiv m_T - A_i - A_G - K$ for J band. Col.(8): Total magnitude defined as $m_T^1 \equiv m_T - A_i - A_G - K - E$ for J band. Col.(9): m_T^0 for H band. Col.(8): m_T^1 for H band.

Table 5. Tully-Fisher distance and Hubble ratio.

Galaxy	cz km s^{-1}	$D_{L\ K}$ Mpc	$D_{L\ K,E}$ Mpc	$H_{0\ K}$ km s^{-1} Mpc^{-1}	$H_{0\ K,E}$ km s^{-1} Mpc^{-1}
(J-band)					
PG0157	48869	251± 37	271± 40	202± 30	187± 27
IR02185	29347	421± 100	441± 105	71± 17	68± 16
IZW23	12224	40± 6	40± 6	313± 49	306± 48
CG1113	13880	118± 20	121± 21	118± 20	116± 20
IC2846	12294	208± 50	213± 51	60± 14	58± 14
IR14060	35060	562± 95	594± 100	64± 11	61± 10
CG1417	21465	244± 44	253± 45	90± 16	86± 16
CG1448	13700	284± 53	291± 55	49± 9	48± 9
N6007	10547	177± 30	181± 30	60± 10	59± 10
IR16533	31808	526± 156	561± 167	62± 18	58± 17
IR23420	26022	493± 83	516± 87	54± 9	52± 9
(H-band)					
PG0157	48869	235± 33	253± 36	216± 31	201± 28
IR02185	29347	421± 97	441± 102	71± 16	68± 16
IZW23	12224	50± 8	51± 8	245± 37	240± 37
CG1113	13880	107± 18	110± 18	131± 22	128± 21
IC2846	12294	189± 44	193± 45	66± 15	64± 15
IR14060	35060	595± 98	629± 103	61± 10	57± 9
CG1417	21465	260± 45	269± 47	84± 15	81± 14
CG1448	13700	369± 67	378± 69	38± 7	37± 7
N6007	10547	209± 34	213± 35	51± 8	50± 8
IR16533	31808	530± 153	558± 161	62± 18	58± 17
IR23420	26022	498± 81	519± 85	53± 9	51± 8

Col.(1): Galaxy name. Col.(2): Redshift in cz. Col.(3): Tully-Fisher distance corrected for K-correction. Col.(4): Tully-Fisher distance corrected for K and E-corrections. Col.(5) and Col.(6): Hubble ratio for the Tully-Fisher distance in Col.(3) and Col.(4), respectively.

Table 6. Results of the CO-line Tully-Fisher relation.

Band	Correction	H_0 km s^{-1} Mpc^{-1}
J	K	60 ± 10
H	K	53 ± 13
J	$K + E$	58 ± 10
H	$K + E$	52 ± 12

Col.(1): Used band. Col.(2): Corrections applied to the total magnitude. K and E stand for K-correction and E-correction, respectively. Col.(3): Determined Hubble constants.

This figure "fig1a.gif" is available in "gif" format from:

http://arXiv.org/ps/astro-ph/0108462v1